

Refractive/diffractive telescope with very high angular resolution for X-ray astronomy

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ABSTRACT

The 0.5 arcsec angular resolution of the Chandra X-Ray Observatory is likely to be the best that a grazing incidence telescope with substantial collecting area will ever attain. We describe a concept for a telescope composed of diffractive and refractive components that transmit rather than reflect X-rays. Therefore, its angular resolution would be relatively insensitive to figure errors and surface roughness. With appropriately selected values for the two focal lengths the chromatic aberration that is inherent in both the diffractive and refractive components individually would compensate each other within a limited but not insignificant energy band. The system has a focal length of about 10^4 km because the refractive component is rather weak. The long focal length requires a very demanding type of formation flying between an optics spacecraft and a detector spacecraft. We simulate the simplest diffractive/refractive imaging system where chromatic aberration is corrected to first order at 6 keV. The angular resolution is expected to be better than a miliarcsec within a 10 % bandwidth. The energy band could be broadened either by employing an array of smaller systems with the same total area or by modifying the diffractive component in situ. The components are lightweight, not difficult to fabricate and can probably be made in a machine shop. We also consider possible sites for the system.

Keywords: X-ray telescopes, X-ray astronomy, diffractive optics, formation flying

1. INTRODUCTION

1.1. Angular resolution

The quest for better angular resolution in all branches of astronomy is never-ending. In the X-ray band its applications include probing closer to the center of activity in AGN's and neutron stars and imaging neighboring stars. It is highly unlikely that the resolution of any future grazing incidence telescope with substantial collecting area will ever be superior to the 0.5 arcsecond resolution of the X-ray telescope aboard the Chandra Observatory. Improving upon Chandra's resolution requires a different technology. A diffractive element in series with a refractive component has been proposed as an X-ray optic that can form images with a resolution better than a miliarcsecond and even down to the level of a microarcsecond^{1,2,3,4}. This paper considers an implementation of diffractive/refractive imaging in more detail. The diffractive component is a Fresnel zone plate. The refractive component is a diverging lens that is made thinner and more transparent at the expense of losing some angular resolution by cutting back the full body into a series of concentric annuli, i.e. a "Fresnel lens".

There are two reasons why the resolution of a diffractive/refractive system should have superior resolution compared to a grazing incidence telescope. One is that the diffraction limit of the system is much better. Because the optics are much lighter weight per unit area their diameter can be much larger for a fixed mass budget. The second reason is that because it transmits rather than reflects X-rays the resolution of a diffractive/refractive system is relatively insensitive to figure errors and surface roughness. It can in fact approach the diffraction limit. Figure errors and surface roughness limit the resolution of a grazing incidence telescope to a level that is much cruder than the diffraction limit.

1.2. Technical challenges: very long focal length and overcoming chromatic aberration

Primarily because of the weak action of the refractive component, diffractive/refractive systems require extremely long focal lengths. The system we consider has a focal length is 10^4 km. This requires that the optics and detector be situated

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on very widely separated spacecraft. However, the separation between spacecraft would not be as large as required by *LISA*, the proposed gravitational wave detection mission.

A high degree of chromatic aberration is characteristic of both diffractive and refractive elements. As described in the referenced papers and the following section, it is possible to reduce chromatic aberration considerably over a limited but significant wavelength band by combining a converging diffractive element with a diverging refractive element that has twice the focal length.

2. THE OPTICS

2.1 The zone plate and refractive lens

The simplest diffractive/refractive X-ray imaging system consists of a Fresnel zone plate in direct contact with a diverging refractive lens. A Fresnel zone plate acts as a converging lens whose focal length is directly proportional to the energy. The zones of the basic zone plate are alternately completely open and completely opaque. The efficiency of the first order image is about 10%. Because the indices of refraction are less than 1 in the X-ray band a diverging refractive lens is convex.

The focal length of the system is driven to large values in order to reduce the opacity of the refractive lens while maintaining the angular resolution. The focal length is proportional to the radius of curvature and for a given aperture the thickness of the lens is inversely proportional to the radius of curvature. Except for very long focal lengths a full body lens would probably be too opaque so the refractive element is actually a Fresnel lens (not to be confused with the Fresnel zone plate) that is formed by cutting back the surface of a full body lens at every point along the sphere where the lens would be too absorbent. This flattens the lens, yielding a concentric series of annular zones. The displacement of the surface is negligible compared to the depth of focus. However, because the annular sections of the Fresnel lens will not be coherent over the instrument's band pass the resolution is degraded compared to the full body lens. The point response function of the Fresnel lens has more power in the wings, particularly at larger angles than the HPD than the full lens. The annuli are analogous to the projected areas of the nested mirror shells in a grazing incidence telescope but the lens' annuli have larger diameters than the mirror shells' projected areas. Therefore their diffraction limit is superior. Furthermore, with immunity to figure errors and surface roughness, we expect the resolution of the diffractive/refractive system to actually be at the diffraction limit determined by the width of the annuli.

The upper limit to the energy is determined by the maximum focal length that can be supported. The low energy limit is a practical issue determined by how thin a beryllium lens could be made structurally sound and mechanically stable. However, in order to penetrate the gas clouds and dust to image closer to the super massive black hole at the center of an AGN the energy should be higher than 3 keV, which establishes a criterion for the lower limit. The fluorescent 6.4 keV Fe line is of special interest because it may exhibit a gravitational red shift that varies with distance from the SMBH. Our estimates assume the mean energy is 6 keV.

The figures below are based upon a system with a diameter of 5 m and a focal length of 10^4 km. The Fresnel lens has 14 zones and is 2 mm thick at each crest. The transmission of the mean thickness of the Be lens (1 mm) is 72% at 6 keV. Except for including its efficiency in estimating the signal, we assume 100% transmission in the simulations of the resolution that appear below. Finite transmission will degrade the resolution slightly. Also, we do not consider the effect of the Fresnel zone plate other than its 10% efficiency as a focusing device and its role in determining the focal length. We do not expect its presence to have a significant effect upon the point response function.

2.2 Chromatic aberration and angular resolution

A zone plate and refractive lens are both highly chromatic by themselves. The focal length of the zone plate is directly proportional to the photon energy and that of the lens to the energy squared. It was shown in the papers referenced that when the focal lens of the diverging lens is twice that of the zone plate, placing the pair in direct contact will correct chromatic aberration over a finite energy band. This is illustrated in Fig. 1

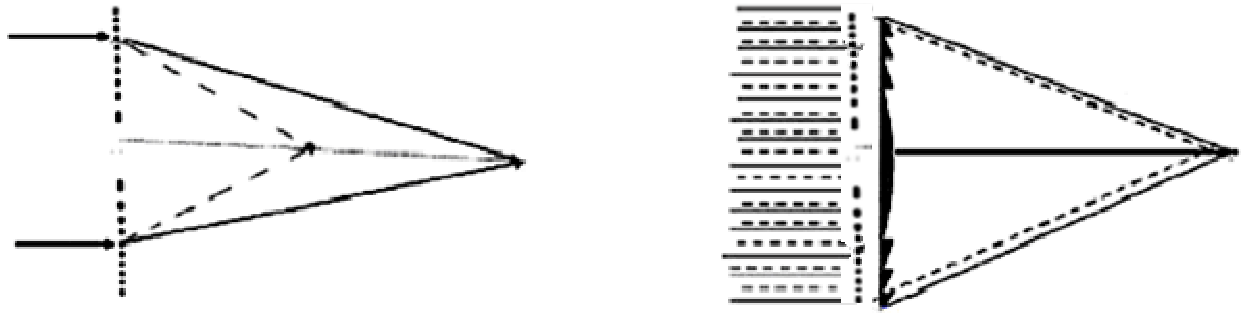


Figure 1. The focal length of a zone plate for a lower energy X-ray (dotted line) is shorter than the focal length of a higher energy ray (solid line) as shown in the left panel. Adding a diverging refractive lens in series can correct the chromatic aberration over a finite energy band (right panel).

The angular resolution as a function of energy and the bandwidth as a function of angular resolution are shown in Fig. 2 for a 5 m diameter system with the refractive lens divided into 14 annuli. At the central energy of 6 keV, the system focal length is at a minimum for a 1st order correction. The angular resolution of the system is then a function of the width of the energy band, which is selected by using the energy resolution of the detector. The detector is likely to be an array of solid-state detectors whose energy resolution is typically about 150 eV.

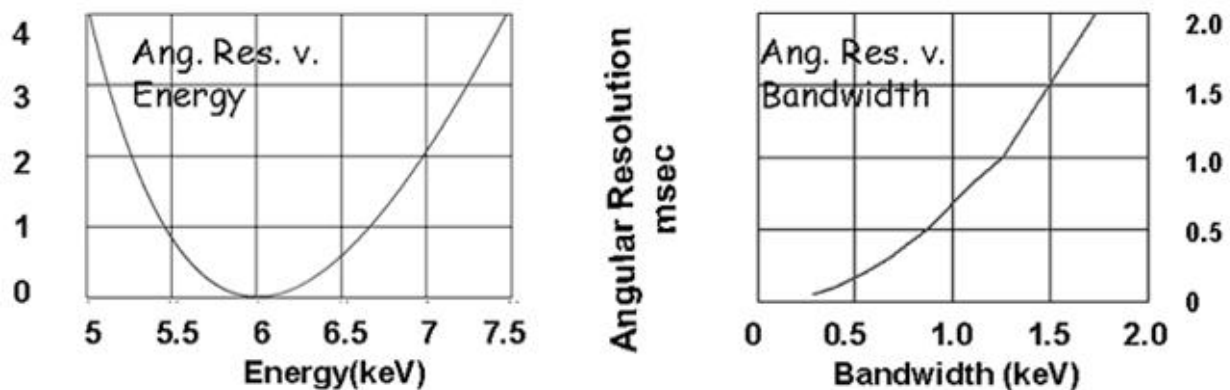


Figure 2. The angular resolution of a 5 m zone plate/refractive Fresnel lens doublet (right panel of Fig. 1) is shown as a function of energy in the left panel. The angular resolution of the system is then a function of how a large a bandwidth is desired.

For example, for the 5 m diameter, 10^4 km focal length system upon which the figure is based the angular resolution is 0.5 miliarcsecond or better but only within a bandwidth of 0.8 keV centered at 6 keV. If an angular resolution of 1.5 miliarcsecond is acceptable then the bandwidth is 1.5 keV. The best angular resolution obtainable with a solid-state detector would be about 35 microarcseconds but for only a 150 eV bandwidth. However, as described below diffraction by the optics can set a higher lower limit. As described in the references much better angular resolution can be obtained (with a higher energy resolution detector and for smaller bandwidth) by separating the zone plate from the lens. That requires formation flying of three widely spacecraft, a level of complexity we do not consider here.

2.3 Comparison with the Chandra Telescope

Although the two telescopes are not really comparable because they operate on vastly different angular scales, ~ 1 arcsecond for Chandra and ~ 1 miliarcsecond for the diffractive/refractive telescope, we compare the properties of a putative 5 m diffractive/refractive contact doublet to those of the Chandra telescope in Table 1. In the absence of a mechanical design, it is difficult to estimate the mass of the doublet. If the zone plate were made of 1 mm Al it would be sufficiently opaque at 6 keV and with half the area consisting of open zones its mass would be 27 kg. The mass of a Be refractive lens with a mean thickness of 1 mm is 36 kg. The total mass of the two optical components is then 63 kg. However, additional mass has to be allowed for structure (i.e. struts, meshes) to support the fragile optics and also for a

deployment mechanism, which unfolds the optics into the 5 m diameter. We assume that their contribution will increase the total mass by a factor of three to 200 kg. The efficiency of the zone plate is 0.1. The mean efficiency of the Be Fresnel lens is 0.72 at 6 keV. Starting from a 5 m aperture, the gross effective area is 1.4 m². The area loss due to structure occluding the aperture is typically 20 % for X-ray telescopes. Therefore the effective area would be about 1.1 m². For the targets that are intense enough for background to not be an issue we can define a figure of merit that consists of the area multiplied by the bandwidth divided by the mass. By this standard, whose significance is limited to strong sources that are completely covered by the field of view, the diffractive/refractive optic is superior to Chandra by a factor of 10.

Table 1
Comparison of 5m Diffractive/Refractive Doublet With the Chandra Telescope

	<u>Chandra</u>	<u>Diff/Ref Doublet</u>
Aperture	1.2 m	5 m
Ang. Resolution	0.5 arcsec	0.7 miliarcsec *
Effective Area	0.1 m ²	1.1 m ² **(est.)
Bandwidth (BW)	7 keV	1 keV
Mass of telescope	1484 kg	200 kg (Al + Be + structure)
Eff Area-BW/Mass	0.47 m ² -keV/ton	5.5 m ² -keV/ton
Minimum Pixel Size	25 microns (0.5")	35 mm (0.0007")
Field of View for 2x Ang. Res.	6 arcmin	40 miliarcsec (2 m detector)***

*For 1 kev BW **Includes zone plate, lens, and structure efficiencies

***Field of View is determined by detector size. It is very large intrinsically.

2.4 Sensitivity and increasing sensitivity with re-imaging

Because of the very large linear dimensions of the pixels background will limit the system's performance. The predominant contribution to the background is cosmic ray interactions. The background of the Chandra ACIS is a good indication of what to expect. It is 4.8×10^{-3} counts-sec⁻¹-cm⁻²-keV⁻¹ at 6 keV⁵. We consider the following example of an object that is imaged and estimate the system's sensitivity. We assume that in order to obtain a satisfactory image, the object should have a statistical significance of 20 standard deviations above background.

Angular size: 6 miliarcseconds	Linear size: 0.3 m x 0.3 m
Detector area occupied by object: 900 cm ²	Energy band: 6 +/- 0.5 keV
Collecting area: 1.1 m ²	Exposure time: 3 x 10 ⁵ seconds
Total background: 13 x 10 ⁵ counts	20 sigma signal: 2.28 x 10 ⁴ counts (within HPD)
Minimum flux: 1.38 x 10 ⁻⁵ counts/sec-cm ² -keV	Min Flux/Crab Neb.: 5 x 10 ⁻⁵

This sensitivity should be high enough to image the nuclei of many AGN's.

The sensitivity could be increased with little loss of angular resolution but with an increase in mass by simply making the optics larger. Enlarging the diameter of optics would create more annuli with decreasing width at the periphery of the refractive lens and zone plate. By preserving the focal length the background is not increased so that the gain in sensitivity is equal to the gain in area.

Re-imaging to increase sensitivity

The sensitivity can be increased with a loss in angular resolution by re-imaging the target source to a smaller focal plane scale. This would not involve the diffractive/refractive optic directly but instead requires that the detector system be a moderate angular resolution grazing incidence telescope rather than an array of solid-state detectors. A detector system that consists of a moderate resolution 1 m telescope plus a small CCD detector is not necessarily more difficult or more

expensive to fabricate than a 1 m solid state array. A modified Wolter telescope optimized for objects at finite distance with, for example, a 10 m focal length and 1 meter diameter would focus upon the focal plane of the diffractive/refractive telescope from a distance of 200 m. The grazing incidence optic reduces the focal plane scale by a factor of 20 and consequently lowers the background by a factor of 400. The efficiency of the grazing incidence telescope would be about 0.3. Therefore, the gain in sensitivity is a factor of 6. This would increase the number of possible targets significantly. However, there will be a loss of angular resolution. A 0.7 milliarcsecond pixel in the focal plane of the diffractive/refractive telescope has a linear size of 3.5 cm, which subtends an angle of 0.6 arcminutes at a distance of 200 m. If the grazing incidence telescope has an intrinsic angular resolution of 1 arcminute the angular resolution would become: $0.7 \cdot \sqrt{1 + 0.6^2} / 0.6 = 1.36$ milliarcseconds for the system overall. The angular divergence of the diffractive/refractive beam is small and the field does not expand significantly along the path from the diffractive/refractive focal plane to the front of the telescope. The size of the field covered by the grazing incidence telescope is essentially equal to its diameter. For a 1 m diameter the field is 20 milliarcseconds, the same as a 1 m area detector.

2.5 Changing the energy band

A single 1 keV band may be too limiting for many objectives. While the energy range cannot be broadened without either losing intensity at the original energy, angular resolution, or field of view it is possible to vary its value. One solution is the rather obvious technique of dividing the area into multiple systems with the same focal length focal length, but tuned to different energies that observe simultaneously. For example, an array of four 2.5 m diameter systems would replace a single 5 m system. Such a change need not increase the total area of the optics or the detector but it requires either an increase in the size of the detector spacecraft envelope to accommodate detectors whose centers are spaced farther apart or a mechanical system that extends the detectors outward.

Another method for varying the energy band that does not allow simultaneous observing in multiple bands is to vary the focal length of the refractive lens without changing the zone plate and relocate the detector spacecraft to a new focal plane position. The focal length of the lens varies as the square of the energy while that of the zone plate varies linearly. Chromatic aberration is corrected to 1st order when the focal length of the refractive lens is the negative of twice the focal length of the zone plate. With a single zone plate and a single lens this condition can be satisfied at only one value of the energy. If the energy of interest is doubled the focal length of the zone plate will double while that of the lens will increase by a factor of 4. However, we require that it increase by only a factor of two. This can occur if a second identical lens is inserted in series. This action should be feasible. The optics by necessity will have to be deployed from a stowed condition. The Be lenses are relatively lightweight and are extremely thin. To prepare for launch it is necessary to fold the 5 m diameter optics into a more compact package, perhaps like a closed umbrella or flower. The optics payload could include multiple lens packages to allow several combinations of lenses in series that can, in combination with a fixed zone plate, correct chromatic aberration in several energy bands, one at time.

3. SIMULATED IMAGES

We consider diffraction by a 5 m diameter Fresnel lens with 14 annular zones of equal area including a 1m central spherical cap. The amplitude as a function of angle of the diffraction pattern of an annulus is given by the following expression where “a” and “b” are the outer and inner radii.

$$A(\Theta) = K \cdot \left[a^2 \cdot \frac{J_1(2\pi a \sin(\Theta) / \lambda)}{2\pi a \sin(\Theta) / \lambda} - b^2 \cdot \frac{J_1(2\pi b \sin(\Theta) / \lambda)}{2\pi b \sin(\Theta) / \lambda} \right]$$

The surface brightness is the square of the amplitude. The angular resolution is usually defined as the angular diameter of the circle that encompasses half the power. Fig. 3 contains plots of the surface brightness of a typical ring and the encircled power as a function of angle for the 6 keV diffraction pattern of the outermost annulus, the innermost section, and for the 5 m Fresnel lens as a whole. Each section contributes equally to the total intensity. The half power diameter is 150 microarcseconds but this applies only to 6 keV photons. In practice the angular resolution is more likely to be determined by the bandwidth selected on the basis of the detector’s energy resolution as discussed in 2.2.

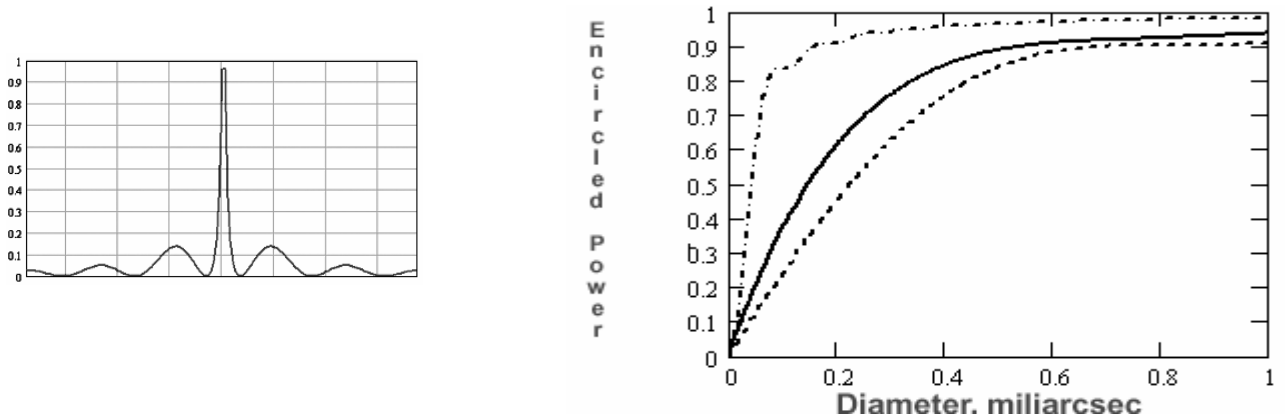


Figure 3. The left panel is the relative surface brightness diffraction pattern of a typical annular ring of a Fresnel lens. The right panel shows, for a 5 m diameter Fresnel lens at 6 keV, the encircled power as a function of angle for the innermost section (dash-dot line), the outermost annular ring (dotted line) and for the entire lens (solid line). The innermost section (a 1 m diameter spherical cap) has better angular resolution than the lens as a whole because it is the section with the largest width. Absorption in the lens and the presence of the zone plate are not considered but they are expected to increase the HPD by only a small amount.

The plateaus that occur in the surface brightness of a single ring are smoothed out when the power from all annuli are summed. We have not included the presence of the zone plate or absorption in the beryllium lens, which is about 56% for 6 keV X-rays where the lens is at its maximum thickness of 2 mm. Including both effects is likely to increase the HPD but only by a small amount.

Figure 4 is a 3D image of the point source response.

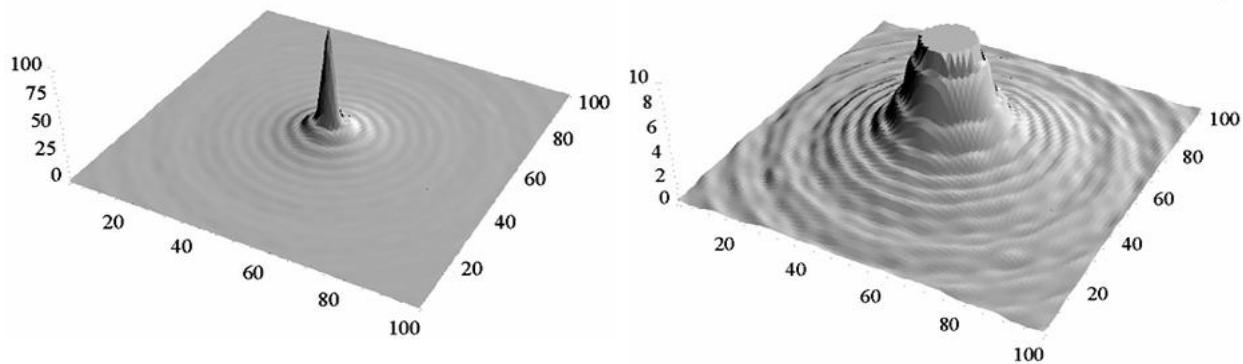


Figure 4. 3D images are shown of the point response of the diffractive/refractive X-ray telescope. The right panel is a factor of 10 enlargement of the left panel.

4. OBSERVATORY ARCHITECTURE

4.1 Sites

Because of the very long focal length at all possible sites in the solar system the gravity gradient will create a significant relative acceleration between the optics and detector spacecraft. The 10^4 km separation precludes even a high Earth orbit as a site because the orbit is likely to be subject to excessive perturbations. The candidates are then an Earth following (or leading) solar orbit and possibly a halo orbit around Sun-Earth L2. The orbital mechanics are more complex at L2 and both spacecraft would require momentum thrusters to remain synchronized on the target. However, the rotation period about L2 is almost independent of the radius of the orbit, which may be advantageous for formation flying. In

solar orbit one spacecraft could be in a free orbit but the trajectory of the other, for example the detector spacecraft, needs to be controlled essentially continuously by thrusters to remain on target. In general, a target direction will have a component both in and normal to the ecliptic plane. The thrusters on the detector spacecraft provide a force vector that when added to the Sun's gravity would result in a net force whose magnitude and direction are what is required for it to follow the target's image around the Sun. For an exposure of one million seconds the two spacecraft will revolve 12 degrees around the Sun. The direction of the thrust would have to change continuously during the exposure.

The amount of thrust needed to compensate for the solar gravity gradient force across a distance of 10^4 km is about 1 mN per ton, which is very modest relative to the capability of current ion drive engines.

4.2 Changing targets: two detector spacecraft

More thrust and more propellant will be required from the ion drive engines to change targets than is needed for station keeping between the detector and optics. We assume, pessimistically, that a target change requires a change in position of the detector spacecraft that is equal to the focal length and that the change is accomplished in the same time as a typical exposure, which we assume to be one million seconds. We further assume that the detector spacecraft accelerates for half the time and decelerates the other half. For a 1 ton spacecraft, the force needed to change target positions by 10^4 km and come to rest in one million seconds is 40 mN. This force is considerably larger than the force needed to stay on target with formation flying but still well within the capability of ion engines.

The observing time lost in changing targets should be minimized. To change targets in half the time requires a force that is four times larger and consequently a much larger ion engine. It would also consume twice as much propellant. The observing time could be utilized much more efficiently with two detector spacecraft. While one observes, the other would be navigating to the next target position. The supply of propellant would last longer and with more modest ion engines the mass of the detector spacecraft would be smaller. With good scheduling we can reduce the distance that the detector has to travel between target positions considerably.

4.3 Station Keeping

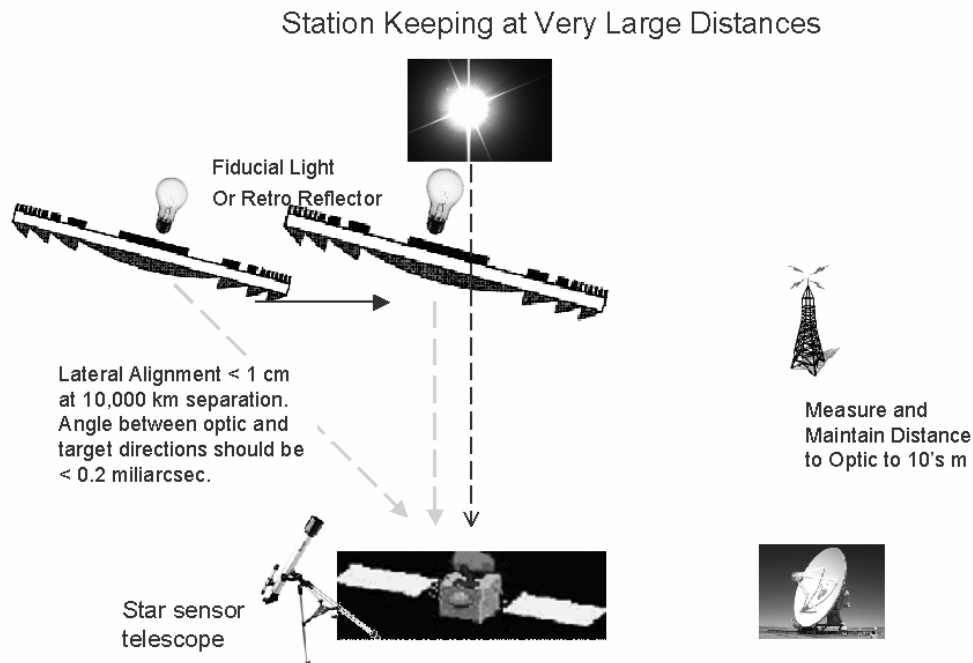


Figure 6. Station keeping between a detector spacecraft and a spacecraft with a diffractive/refractive X-ray telescope. The direction vector from the detector to the center of the lens has to coincide with direction to the target.

Formation flying at a distance of 10^4 km is the most challenging aspect of the proposed observatory. As seen from the detector, the optics assembly must be centered on the direction to the target. Fortunately, spacecraft pointing accuracy is not an issue. The optic is a very thin lens, and its field of view is very large compared to the detector-limited field of view. The position of the image is not sensitive to moderate changes in pointing as long as the coordinates of the center of the lens are aligned with the target. The requirement on alignment of optics and target is set by the angular resolution. For a misalignment of 0.2 milliarcsec, the lateral position tolerance is 1 cm. With *a posteriori* image reconstruction, the requirement is on knowledge, with control an order of magnitude more lenient. The tolerance on the separation between the two is rather lenient because the 0.7 milliarcsecond depth of field is about 100 m. Fig. 5 is a cartoon of station keeping between the detector and optics spacecraft. Although the figure gives the opposite impression, we would place the major responsibility for station keeping on the detector spacecraft, which is more compact. The optics spacecraft would participate passively by displaying and broadcasting signals. The 1 cm tolerance on the lateral alignment translates into a 0.2 milliarcsecond angular tolerance between the directions of the optics and the target as seen from the detector. The alignment can be measured to the required accuracy with a special optical star sensor aboard the detector spacecraft as long as there is a bright star near the target for guidance and a set of optical sources on the optics spacecraft. The separation between detector and optics can be determined with excellent accuracy by measuring the round-trip propagation time of a modulated radio signal from the detector to a transponder on the optics spacecraft.

Like all X-ray detectors that will participate in formation flying missions, the field of view of these detectors will be collimated to about a degree to limit background from diffuse X-rays, other sources, and stray light in general.⁶ With the collimator, background from X-ray effects will much less than the background from cosmic ray interactions that were used in 2.4 to estimate the sensitivity.

5. SUMMARY AND CONCLUSIONS

Diffraction/refractive optics is put forth as the likely successor to grazing incidence optics for general-purpose high angular resolution imaging in the X-ray band. Milliarcsecond resolution should be within reach. The chromatic aberration that is characteristic of the diffractive and refractive components individually can vanish within a narrow but significant, $\sim 15\%$, energy band when the two are used in combination with the appropriate focal lengths. Multiple energy bands are accessible either by dividing the optics into an array of smaller devices with the same total area or by modifying the refractive component in situ. The optical system is light-weight and should be relatively inexpensive and easy to construct. The most challenging aspect of applying this technology is supporting the extremely long focal lengths, i.e. the order of 10^4 km or longer, which requires formation flying across large separations with centimeter accuracy. Large format detectors are required but they are feasible with current technology. With exposures of 3×10^5 seconds or longer the sensitivity will be sufficient to image a large number of AGNs and compact binary systems much closer to their centers of activity.

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